

Ion temperature profile stiffness: non-linear gyrokinetic simulations and comparison with experiment

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Abstract. Recent experimental observations at JET show evidence of reduced ion temperature profile stiffness at low magnetic shear (\hat{s}) in the presence of flow shear. Non-linear gyrokinetic simulations are performed, aiming to investigate the physical mechanism behind the observations. The sensitivity of profile stiffness to the variations of plasma parameters experimentally observed when transitioning to the low-stiffness regime is assessed. It is found that non-linear electromagnetic effects, even at low β_e , can significantly reduce the profile stiffness, although not by a degree sufficient to explain the experimental observations. The effect of toroidal flow shear itself is not predicted by the simulations to lead to a significant reduction in flux due to significant parallel gradient velocity destabilisation. For the majority of discharges studied, the simulated and experimental ion heat flux values do agree within reasonable variations of input parameters around the experimental uncertainties. However, no such reasonable agreement is obtained for the discharge with the highest logarithmic ion temperature gradient. The simulated stiffness level is thus higher than observed for this regime, when assuming pure toroidal rotation.

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1. Introduction

It is well established that one of the primary limitations of tokamak energy confinement is ion-Larmor-radius-scale turbulent transport driven by background pressure gradients [1]. The ion-temperature-gradient (ITG) instability in particular has been long identified as a ubiquitous unstable mode in tokamak plasmas [2, 3, 4, 5], and is primarily responsible for ion heat losses. The instability saturates in a non-linear state in conjunction with non-linearly excited zonal-flows, forming a self-organised turbulent system which sets the transport fluxes [6].

In addition to self-organised zonal-flows, the application of external flow shear is predicted to suppress turbulence through two broad mechanisms: decorrelation of the turbulent structures in the non-linear phase once the shearing rate is comparable with or exceeds the inverse non-linear autocorrelation time; suppression of the driving linear modes by continuously shifting the mode from the most unstable spatial scale to nearby, more stable spatial scales [7, 8]. Flow shear has been observed experimentally to be correlated with tokamak transport barriers [9, 10, 11]. Non-linear gyrofluid simulations with adiabatic electrons have predicted turbulence quenching above $\gamma_E/\gamma_{max} = 1 \pm 0.3$ [12, 13], where for purely toroidal rotation the normalised $E \times B$ shear rate $\gamma_E \equiv \frac{r}{q} \frac{d\Omega}{dr} / (\frac{v_{th}}{R})$, and γ_{max} is the maximum linear growth rate in the absence of rotation. Later gyrokinetic simulations, including cases with kinetic electrons, predicted that quenching occurs at somewhat higher (but similar) flow shear compared to the gyrofluid simulations, at $\gamma_E/\gamma_{max} = 2 \pm 0.5$ [14, 15, 16]. According to results in Ref.[15], this quench behaviour is independent of the adiabatic or kinetic electron assumption. However, when including kinetic electrons, the trapped electron drive tends to raise the instability growth rates even for ITG turbulence. Therefore, when including kinetic electrons (which is more realistic) the resultant higher γ_{max} necessitates a higher value of γ_E compared with the adiabatic electron case to reach a similar γ_E/γ_{max} ratio and quench the turbulence. The seeming robustness of the transport quench has motivated formulations of effective growth rate reduction due to the flow shear in the mixing length rule of quasilinear transport models such as GLF23 and TGLF [17, 18].

The abovementioned quench results were obtained in simulations which did not include a self-consistent parallel velocity gradient (PVG) in the system, which can be destabilising [19, 20]. When PVG destabilisation is included, simulations have shown that they can limit the transport quench [12, 21, 15]. It is thus important to incorporate the effects of PVG destabilisation in transport models when comparing modelling predictions with experiments that have significant flow shear. For pure toroidal rotation, the degree of the PVG destabilisation depends on the magnetic geometry since then $\gamma_p = \frac{q}{\epsilon} \gamma_E$, where γ_p is the PVG shear rate, and $\epsilon \equiv r/R$.

Experimental results of flow shear stabilisation of core turbulence are not systematic. While improved core confinement in hybrid scenarios due to flow shear has been observed at DIII-D [22], a counterexample is evident from experiments involving JET standard H-modes which showed a lack of variation in core-confinement even when

significantly varying the rotation profiles and maintaining constant total power [23].

It has been recently observed in dedicated experiments at JET that ion temperature profile stiffness can be reduced at low normalised radii ($r/a < 0.5$), in disagreement with non-linear ITG turbulence modelling [24, 25, 26]. This has been hypothesised to be related to the correlation between low magnetic shear (\hat{s}) and increased flow shear in the low stiffness discharges. The term ‘stiffness’ is defined here as the local gradient of the gyro-Bohm normalised ion heat flux with respect to R/L_{Ti} (normalised inverse gradient length). The observations concentrated on $\rho = 0.33$ and $\rho = 0.64$ (where ρ is the normalised toroidal flux coordinate). At $\rho = 0.33$, the stiffness is observed to transit from high to low when the flow shear was increased. However, at $\rho = 0.64$, stiffness is observed to be high irrespective of flow shear. A previous non-linear gyrokinetic study based on the recent JET discharges at $\rho = 0.33$, as detailed in Ref.[25], reported only a ITG threshold shift with rotation, as opposed to a decrease in stiffness as observed. Additional observations made in Refs. [24, 25, 26] pertinent to this work are as follows: at low rotation at $\rho = 0.33$, the observed stiffness level is higher than the gyrokinetic simulation predictions; furthermore, the observed ITG threshold is lower than the non-linear gyrokinetic prediction, questioning the manifestation of the Dimits shift [27] predicted by non-linear simulations.

In this paper, we extend this previous work and aim to investigate whether the experimental observations can be understood through gyrokinetic modelling. Understanding these effects could allow the identification of a potential actuator for core T_i control. For the analysis, linear and non-linear simulations are carried out with the GENE code [28]. Four JET discharges (with the previous carbon wall) were selected: 70084, 66130, 66404, and 73221. Discharges 66130 and 66404 are situated on the ‘high-rotation, low-stiffness branch’ at $\rho = 0.33$ seen in Fig.1 in Ref.[25], and partially reproduced here for convenience in Fig.1. Discharge 70084 is a low flux, low rotation discharge selected to provide a data point near the turbulence threshold. Discharge 73221 is a high flux, low rotation discharge situated on the ‘low-rotation, high-stiffness branch’ at $\rho = 0.33$, as shown in Fig.1. The specific questions which we investigate are the following:

- (1) Is the experimentally observed stiffness reduction for the high-rotation discharges at $\rho = 0.33$ consistent with gyrokinetic non-linear simulation predictions? Which plasma parameters have the highest impact on the stiffness level for ITG turbulence? Is there sufficient leeway in the plasma parameters due to uncertainties such that the experimental observations and non-linear simulation predictions can be reconciled?
- (2) Is the *lack* of experimentally observed stiffness reduction for the high-rotation discharges at $\rho = 0.64$ consistent with gyrokinetic non-linear simulation predictions?
- (3) Can the experimentally extrapolated turbulence threshold be reconciled with the non-linear turbulence threshold including the Dimits shift, given reasonable uncertainties in the plasma parameters?
- (4) Can the seeming high stiffness in the ‘low-rotation, high-stiffness’ branch at $\rho = 0.33$

be reconciled with the non-linear simulations, given reasonable uncertainties in plasma parameters?

The discharges were reanalysed with the CRONOS suite of integrated modelling codes [29] to identify any differences in parameters apart from rotation and R/L_{Ti} within the chosen discharge set - such as T_e/T_i , R/L_n , β_e , and fast particle content - which may lead to the observed differences in ion heat flux and R/L_{Ti} . The sensitivity of the ion heat flux and stiffness to each of these parameters was tested with GENE in dedicated R/L_{Ti} scans. Finally, complete simulations - i.e. collisional, electromagnetic, multi-species, and with rotation - were carried out at both $\rho = 0.33$ and $\rho = 0.64$.

The rest of the paper is organised as follows. In section 2 the GENE gyrokinetic code is briefly reviewed, as are the base parameters of the simulated discharges. In section 3 the results at $\rho = 0.33$ are shown. In section 4 the results at $\rho = 0.64$ are shown. Conclusions are presented in section 5.

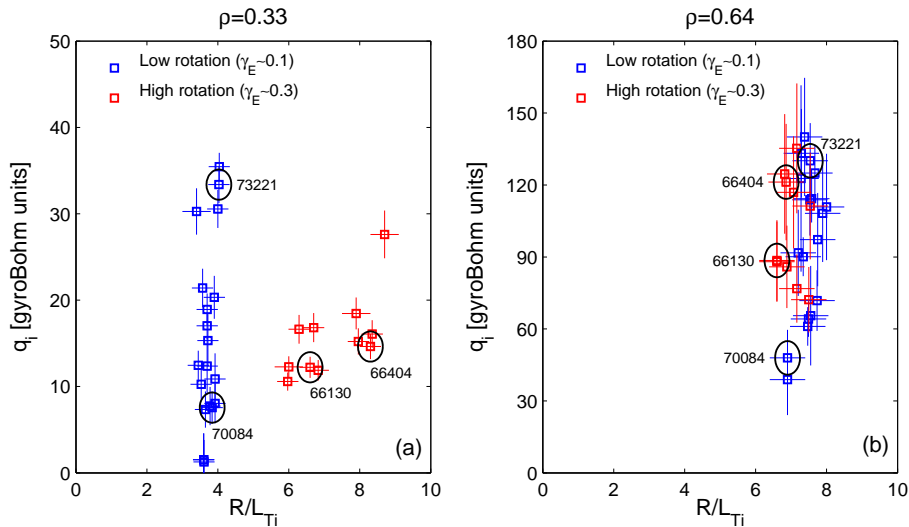


Figure 1. Partial reproduction of data presented in Ref.[25] displaying the separation between high and low stiffness regimes at $\rho = 0.33$ (a) for discharges with low and high rotation respectively. At $\rho = 0.64$ (b) no significant separation of the stiffness behaviour is evident. The heat fluxes are in gyroBohm normalised units, $q_{GB} = T_i^{2.5} n_i m_i^{0.5} / e^2 B^2 R^2$. The specific discharges studied in this paper have been circled.

2. GENE simulations and discharge parameters

GENE solves the gyrokinetic Vlasov equation, coupled self-consistently to Maxwell's equations, within a δf formulation [30]. Computational efficiency is gained by solving in field line coordinates. x is the radial coordinate, z is the (poloidal) coordinate along the field line, and y is the binormal coordinate. Both an analytical circular geometry model (derived in Ref.[31]) as well as numerical geometry were used in this work. The circular geometry model avoids the order $\epsilon = a/R$ inconsistency present in the often

Table 1. Discharge dimensional parameters. The values are averaged between 9.5-10.5 s for discharges 70084 and 66130, between 6.5-7.5 s for discharge 66404, and between 7-8 s for discharge 73221. Quoted errors are statistical, and do not include possible systematic errors.

Shot no.@location	B [T]	I_p [MA]	T_i [keV]	T_e [keV]	n_e [10^{19} m^{-3}]
70084@ $\rho = 0.33$	3.5	1.8	2.01 ± 0.02	2.16 ± 0.1	2.6 ± 0.2
66130@ $\rho = 0.33$	3.1	1.5	2.58 ± 0.04	3.3 ± 0.3	3.37 ± 0.24
66404@ $\rho = 0.33$	3.5	1.8	3.1 ± 0.13	3.61 ± 0.08	2.3 ± 0.1
73221@ $\rho = 0.33$	3.5	1.8	1.84 ± 0.04	2.44 ± 0.03	2.45 ± 0.16
70084@ $\rho = 0.64$	3.5	1.8	1.08 ± 0.02	1.27 ± 0.05	2.3 ± 0.3
66130@ $\rho = 0.64$	3.1	1.5	1.38 ± 0.03	1.5 ± 0.24	2.8 ± 0.3
66404@ $\rho = 0.64$	3.5	1.8	1.34 ± 0.08	1.66 ± 0.14	1.51 ± 0.07

applied $s-\alpha$ model, but does not include a Shafranov shift. For the numerical geometry, the FINESSE code was used to solve the extended Grad-Shafranov equation including toroidal rotation [32]. All simulations carried out were local, justified since $1/\rho^* \sim 500$ for the range of plasma parameters studied here [33, 34]. Both linear and non-linear simulations were performed. In the linear mode, an eigenvalue solver was used to compute multiple modes for each point in parameter space [35, 36]. In the presence of rotation, when no time-independent eigenmodes can form, a complementary initial value solver was used.

Four discharges from the data-set presented in Ref.[25] were analyzed at $\rho = 0.33$ and $\rho = 0.64$, where ρ is the normalised toroidal flux coordinate. The discharges are 70084, 66130, 66404, and 73221. Discharge 70084 corresponds to a representative low rotation, low flux discharge. 66130 and 66404 are discharges further up on the ‘high rotation, decreased stiffness’ curve as seen in Fig.1. 73221 is a high flux, low rotation discharge situated on the ‘low-rotation, high-stiffness branch’ at $\rho = 0.33$, as shown in Fig.1. The kinetic profiles of the four discharges were spline fitted and interpretative runs were carried out with the CRONOS integrated modelling suite of codes [29] for the equilibrium calculations and q -profile calculations. The kinetic profiles were then averaged over 1 s centered around 10/10/7/7.5 s respectively for calculations of the gradient lengths and other quantities such as β_e . The parameters are shown tables 1-2. Discharge 73221 was only analysed at $\rho = 0.33$, for the investigation of the seemingly high stiffness of the low rotation branch. The $\langle Z_{eff} \rangle$ values correspond to Bremsstrahlung measurements. Since the precise Z_{eff} profiles are not known, the sensitivity of the transport predictions to the range of reasonable Z_{eff} at $\rho = 0.33$ is explored in section 3.7. ν^* is the normalised collisionality: $\nu^* \equiv \nu_{ei} \frac{qR}{\epsilon^{1.5} v_{te}}$, with $\epsilon = a/R$ and $v_{te} = \sqrt{\frac{T_e}{m_e}}$. Note that the data presented in table 2 was processed *separately and independently* from the values quoted in Ref.[24, 25] and shown in Fig.1. The R/L_{Ti} values in table 2 and Fig.1 agree within error bars.

The agreement between the q -profiles obtained by CRONOS interpretative simulations and the measured q -profiles is satisfactory, as seen in Fig.2. The average discrepancy between the interpretative and measured q -profile values at $\rho = 0.33$ and 0.64 is $\sim 10\%$, within the estimated uncertainty of the q -profile measurements.

Table 2. Discharge dimensionless parameters. The \hat{s} and q values are calculated by CRONOS interpretative simulations, assuming neoclassical diffusion. The values are averaged between 9.5-10.5 s for discharges 70084 and 66130, between 6.5-7.5 s for discharge 66404, and between 7-8 s for discharge 73221.

Shot no.@location	\hat{s}	q	T_e/T_i	R/L_{Ti}	R/L_{Te}	R/L_{ne}	β_e [%]	ν^*	$\langle Z_{eff} \rangle$	$M[v_{tor}/c_s]$
70084@ $\rho = 0.33$	0.7	1.7	1.08 ± 0.04	3.5 ± 0.5	3.8 ± 0.6	1.4 ± 0.4	0.19 ± 0.01	0.07	2.2 ± 0.1	0.09
66130@ $\rho = 0.33$	0.7	1.8	1.25 ± 0.13	6 ± 0.4	6.5 ± 1	2.4 ± 1	0.46 ± 0.09	0.04	1.8 ± 0.1	0.31
66404@ $\rho = 0.33$	0.4	1.8	1.14 ± 0.06	8.6 ± 0.9	5.5 ± 0.8	3.8 ± 0.4	0.35 ± 0.07	0.02	2.2 ± 0.1	0.19
73221@ $\rho = 0.33$	0.7	1.5	1.33 ± 0.02	3.8 ± 0.4	5.4 ± 0.2	2.8 ± 0.3	0.2 ± 0.02	0.055	2.2 ± 0.1	0.07
70084@ $\rho = 0.64$	1.3	3	1.18 ± 0.05	7.2 ± 0.2	6.4 ± 1	1.8 ± 0.8	0.096 ± 0.01	0.16	2.2 ± 0.1	0.03
66130@ $\rho = 0.64$	1.5	3.5	1.1 ± 0.2	6.8 ± 0.3	8.5 ± 3	1.8 ± 1.4	0.18 ± 0.04	0.1	1.8 ± 0.1	0.23
66404@ $\rho = 0.64$	1.4	2.9	1.23 ± 0.13	6.9 ± 0.4	10 ± 1.6	2.1 ± 0.9	0.08 ± 0.01	0.05	2.2 ± 0.1	0.15

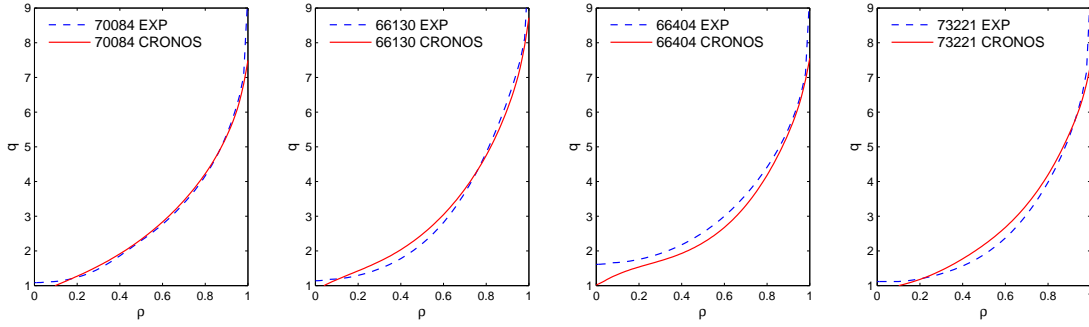


Figure 2. Comparison between CRONOS interpretative simulation q -profiles and experimental q -profiles. The profiles are averaged between 9.5-10.5 s for discharges 70084 and 66130, between 6.5-7.5 s for discharge 66404, and between 7-8 s for discharge 73221.

The experimental q -profiles were obtained by EFIT constrained by either Faraday rotation measurements (discharges 70084 and 73221) or motional Stark effect (MSE) measurements (discharges 66130 and 66404).

In the GENE simulations, typical grid parameters were as follows: perpendicular box sizes $[L_x, L_y] = [170, 125]$ in units of $\rho_s \equiv c_s/\Omega_{ci} = \sqrt{T_e/m_i}/(eB/m_i)$, perpendicular grid discretisations $[n_x, n_y] = [192, 48]$, 24 point discretisation in the parallel direction, 32 points in the parallel velocity direction, and 8 magnetic moments. Extensive convergence tests were carried out for representative simulations throughout the parameter space spanned in this work. The lack of convergence of the heat fluxes with increasing n_y as reported for GYRO [37] simulations of discharge 70084 in Ref.[25] - associated with increasing zonal flows - was not encountered here. In our cases the convergence with n_y was well behaved. The difference may stem from the different treatment of the radial boundary conditions in the GENE and GYRO simulations. Further investigation is necessary to ascertain this. The heat fluxes shown in the following sections are in gyroBohm normalised units, $q_{GB} = T_i^{2.5} n_i m_i^{0.5} / e^2 B^2 R^2$. k_y is in units of $1/\rho_s$. These heat fluxes correspond to time averaged values over the saturated state of the GENE simulations. The statistical flux variations due to intermittency are for clarity not explicitly shown as error bars. This variation is typically 5 – 10% for our parameters. γ and γ_E are in units of c_s/R where $c_s \equiv \sqrt{T_e/m_i}$. All rotation is considered to be

purely toroidal unless specifically mentioned otherwise. For the low and high rotation discharges it was assumed that $\gamma_E = 0.1$ and 0.3 respectively, at both $\rho = 0.33$ and $\rho = 0.64$. These are representative γ_E values for the low and high stiffness discharges from the dataset in Ref.[25].

3. Simulations at $\rho = 0.33$

In this section, we isolate the effect of various parameters on ion profile stiffness and critical threshold, at $\rho = 0.33$ (where the transition to low stiffness at high rotation was observed). These parameters are: q , \hat{s} , rotation, effect of rotation on the magnetohydrodynamic (MHD) equilibrium, fast particle content, R/L_n , β_e , and Z_{eff} . We then proceed to realistic simulations of 70084, 66130, 66404 and 73221 for a full comparison between the gyrokinetic predictions and experimental ion heat fluxes. These simulations simultaneously include: numerical geometry, collisions, electromagnetic effects, Z_{eff} (by including a carbon species), and realistic T_e/T_i .

3.1. Stiffness and threshold sensitivity to q and \hat{s}

While the linear ITG turbulence threshold increases with \hat{s}/q [38], the stiffness (i.e. the rate of change of the gyro-Bohm normalised ion heat flux with respect to R/L_{Ti}) decreases in non-linear ITG simulations with both decreasing \hat{s} and decreasing q . For decreasing \hat{s} , the reduced stiffness has been shown to be correlated with increased coupling to zonal flows [39]. For decreasing q , this is due to an decreased downshift (compared with the peak in the linear spectrum) in the peak wavenumber of the turbulence spectrum, indicating decreased correlation lengths [40, 41, 42]. These sensitivities are shown in Fig.3. For example, we can see that for both the $\hat{s}/q = 0.6/1.3$ and $\hat{s}/q = 1/2$ cases the turbulent threshold is similar while the stiffness is lower for the $\hat{s}/q = 0.6/1.3$ case.

We will deliberately make an optimistic assumption that $\hat{s}/q = 0.2/1.3$ throughout all the subsequent parameter scans carried out at $\rho = 0.33$ in this work. For the numerical geometry cases, this was done by modifying the current profile input into CRONOS such that at $\rho = 0.33$ values of $\hat{s}/q = 0.2/1.3$ were obtained following the solution of the Grad-Shafranov equation. The choice of assuming $\hat{s}/q = 0.2/1.3$ is to ensure that we are in a ‘low- \hat{s} regime’, which has been hypothesised to be an important factor in the stiffness reduction, based on the observed correlation between low stiffness and low- \hat{s} throughout the data set in Ref.[25]. An added advantage is that this choice is optimistic regarding stiffness reduction. Thus, if the non-linear gyrokinetic simulations do not display the same degree of low stiffness as experimentally observed even with $\hat{s}/q = 0.2/1.3$ - as will indeed be shown - then this choice ensures that uncertainties in the q -profile cannot be invoked to suggest that the \hat{s} and q values used were not low *enough* to obtain reduced stiffness. For the GENE simulations at $\rho = 0.64$ shown in section 4, the CRONOS calculated q and \hat{s} values were taken for each discharge.

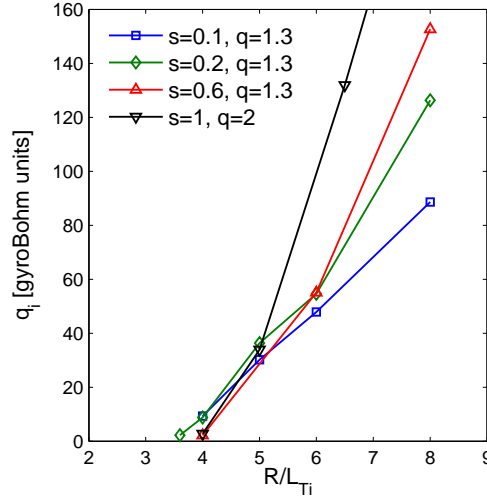


Figure 3. Non-linear electrostatic collisionless GENE R/L_{Ti} scans for various levels of \hat{s} and q -profile with circular geometry at $\rho = 0.33$. $R/L_{Te} = 5$, and $R/L_n = 1.1$.

The discussion of the sensitivity of the linear threshold to q brings us to an important point. In Refs.[24, 25], it was pointed out that the measured turbulence threshold of the low-rotation discharges in the data set were lower than the predicted non-linearly upshifted (Dimitis shift) [27] thresholds. These thresholds were predicted by non-linear simulations based on discharge 70084 performed with the GS2 non-linear gyrokinetic code [43]. This result questioned the Dimitis shift paradigm. The q value used for these previous simulations was $q = 1.3$, based on the processed data at the time. However, the data processing methodology for obtaining q -profiles using Faraday rotation constraints at JET [44] has since been improved, leading to a revision of the measured q -profile value to $q = 1.7$ at $\rho = 0.33$ for $t \sim 10$ s for discharge 70084. The impact of this difference in q on the linear and non-linear thresholds as predicted by the gyrokinetic codes is significant. This is shown in Fig.4. In the figure, the GS2 predicted ion heat fluxes for the $\hat{s}/q = 0.6/1.3$ case (as shown in Ref.[24]) is compared with the analogous GENE simulations. The agreement between the codes is good, apart from the zone near the threshold. This difference is likely to be due to the different methods used to calculate the geometry: analytical circular in GENE, and $\hat{s} - \alpha$ geometry in GS2. However, the non-linear threshold for $\hat{s}/q = 0.6/1.3$ in both codes is approximately $R/L_{Ti} \sim 4.5$, above the experimental threshold from Ref.[25]. These curves can then be compared with the R/L_{Ti} scan (carried out with GENE) with the revised values $\hat{s}/q = 0.7/1.7$. In this case, the linear threshold is $R/L_{Ti} = 2.7$, and the non-linear threshold following the Dimitis shift is at $R/L_{Ti} \sim 3.5 - 4$, in much better agreement with the experimental data. Consistency of the $\hat{s}/q = 0.7/1.7$ values with both the revised experimental q -profile and CRONOS simulations is thus suggestive that the Dimitis shift paradigm is in fact now supported by the experimental observations. However, the high sensitivity of the turbulence thresholds to the precise \hat{s} and q values leads us to a more conservative conclusion that no firm statement is justified regarding the consistency of

the experimental data with the non-linear Dimits shift. The various values of \hat{s} and q used in the R/L_{Ti} scans in Fig.4 (including the $\hat{s}/q = 0.2/1.3$ values subsequently used in this section) can be seen to constitute a sensitivity test of the ‘reasonable’ range of q and \hat{s} in lieu of rigorous error bars. The one clear conclusion from this sensitivity scan, is that there is no clear *disagreement* between the experimental data and the non-linear threshold upshifted due to the Dimits shift.

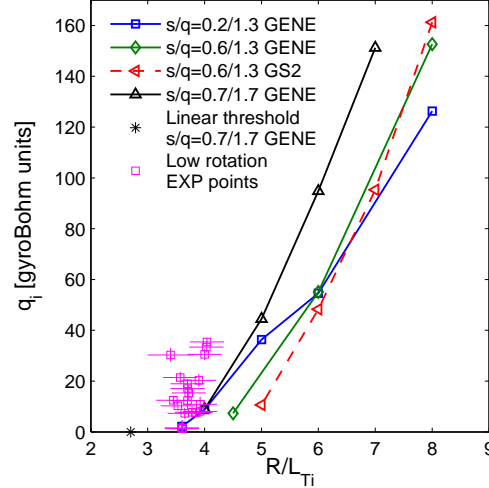


Figure 4. Comparison between non-linear electrostatic collisionless GENE and GS2 R/L_{Ti} scans with the low rotation data from the data-set in Ref.[25] for various levels of \hat{s} and q . The GENE runs are with circular geometry at $\rho = 0.33$, the GS2 runs with $\hat{s} - \alpha$ geometry. $R/L_{Te} = 5$, and $R/L_n = 1.1$.

While the non-linear turbulence threshold extrapolated from the $\hat{s}/q = 0.7/1.7$ curve in Fig.4 matches the experimental threshold, the simulated stiffness level is seemingly lower than the experimental trend. The possibility that this discrepancy can be explained by the differences in T_e/T_i between the low flux and high flux points in the low rotation branch - which impact the critical threshold - is explored in the more comprehensive simulations shown in section 3.7.1.

3.2. Stiffness sensitivity to rotation

In this subsection we isolate the effect of rotation on stiffness, assuming pure toroidal rotation. This assumption is justified for JET discharges with significant NBI. Collisionless, electrostatic simulations based on 70084 parameters (assuming $\hat{s}/q = 0.2/1.3$) are carried out, applying analytical circular geometry [31]. The predicted gyroBohm normalised ion heat fluxes from the R/L_{Ti} scans are shown in Fig.5. The sensitivity to γ_E is examined. Even for $\gamma_E = 0.6$, double the highest level of flow shear achieved in the reference data set from Ref.[25], the simulated level of reduced stiffness is significantly less than the experimental observation, as seen by the direct comparison with the reference data. However, interesting effects related to the competition between stabilising $E \times B$ shear and destabilising parallel velocity gradient (PVG) modes -

particularly in the vicinity of the threshold - are observed. At low R/L_{Ti} , the PVG destabilisation can dominate over the ITG turbulence, reducing stiffness in that region of parameter space. Due to the PVG destabilisation, the fluxes do not continue to decrease towards the ITG instability thresholds. This is seen in Fig.5a by examining the various curves at fixed R/L_{Ti} . At low R/L_{Ti} , the fluxes rise with γ_E due to PVG drive. However at higher R/L_{Ti} , the fluxes decrease with R/L_{Ti} due to the ITG stabilisation by perpendicular $E \times B$ flow shear dominating over the PVG destabilisation. In Fig.5b the parallel velocity gradients were artificially removed from the system, and the picture reverts to a threshold shift. Note that particularly for the (red) $\gamma_E = 0.3$ and (black) $\gamma_E = 0.6$ curves the apparent reduced slope near threshold is not necessarily indicative of reduced stiffness in that regime, since the actual effective non-linear threshold may lie between the precise values of the R/L_{Ti} values chosen for the simulations.

For pure toroidal rotation, the relative importance of PVG destabilisation versus $E \times B$ stabilisation is sensitive to the geometric parameter q/ϵ (where $\epsilon \equiv r/R$) [45]. As q/ϵ increases, the field lines are increasingly projected onto the toroidal direction. In Fig.6, a q/ϵ scan is carried out by varying ϵ in the various R/L_{Ti} scans. Simulations with $\epsilon = 0.11, 0.15$ assuming circular geometry were performed, as well as an $\langle \epsilon \rangle \equiv \langle r \rangle / R = 0.13$ case from the flux surface averaged minor radius at $\rho = 0.33$ using numerical geometry from the HELENA [46] equilibrium in the CRONOS simulation of discharge 70084. The R/L_{Ti} values in the plots corresponding to numerical geometry are defined here with respect to the averaged midplane minor radius. The relative strength of the PVG destabilisation is seen to weaken as expected with decreasing q/ϵ , until an almost pure threshold shift case is reached with $q/\epsilon = 8.7$.

The interplay between PVG destabilisation and $E \times B$ stabilisation demands that PVG modes are correctly accounted for in reduced transport models - such as in gyrokinetic or gyrofluid based quasilinear models. It is insufficient in such formulations to include a growth rate quench model due to $E \times B$ stabilisation without simultaneous self-consistent and validated modelling of the PVG modes. Correct modelling near the turbulent thresholds is particularly critical for high temperature tokamaks, such as ITER. This is because the normalised fluxes are expected to be in the vicinity of the turbulence thresholds due to the $T_i^{5/2}$ normalisation dependence.

Finally, we note that the observed Dimits shift [27] in these cases is only $\Delta(R/L_{Ti}) \approx 0.5$, or alternatively $\frac{\Delta(R/L_{Ti})}{R/L_{Tcrit}} \approx 15\%$. These values are similar to the $\frac{\Delta(R/L_{Ti})}{R/L_{Tcrit}} \approx 20\%$ shifts observed in previous realistic simulations [47]. The linear threshold was calculated by extrapolation to zero-growth-rate of linear R/L_{Ti} scans with GENE. The linear threshold in the numerical geometry case is nearly identical to the circular geometry case.

In summary, the GENE simulations do not predict a significant reduction in stiffness due to flow shear, even with our deliberate choice of $\hat{s} = 0.2$. However, the reduction in flux due to the flow shear is not negligible. As suggested by Fig.6c and as shown in section 3.7, a significant reduction of flux due to flow shear is only seen when both the effect of PVG destabilisation is artificially reduced, and γ_E is increased beyond the

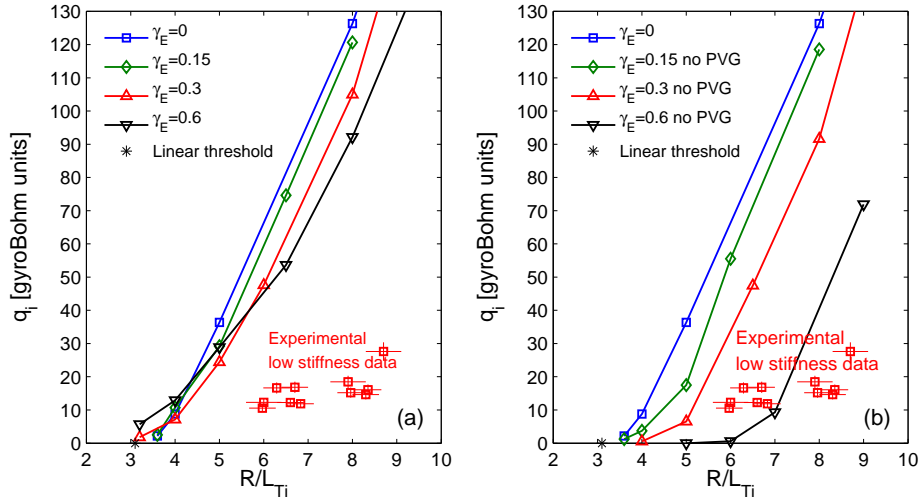


Figure 5. Non-linear GENE R/L_{Ti} scans based on 70084 parameters at $\rho = 0.33$ ($q/\epsilon = 11.8$ for circular geometry) and various levels of γ_E [c_s/R]. Runs including PVG destabilisation are shown in (a). Runs ignoring PVG destabilisation are seen in (b). All runs were electrostatic, collisionless, and with circular geometry. The results are compared with the low stiffness data at $\rho = 0.33$ from Ref.[25].

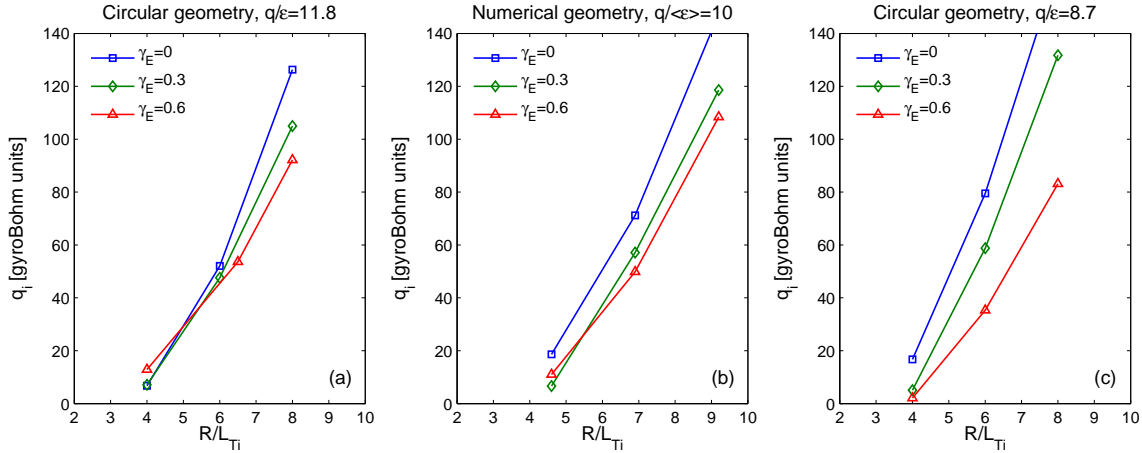


Figure 6. q/ϵ sensitivity of the PVG destabilisation as seen in R/L_{Ti} scans of ion heat flux. As q/ϵ is progressively raised, the γ_E induced stabilisation can not only be reduced but can even be reversed in the region of the instability threshold. Runs were electrostatic, collisionless, and with circular geometry.

experimental values expected from the toroidal flow shear.

3.3. Effect of rotation on the equilibrium

The effect of rotation on stiffness through the impact of the centrifugal force on the plasma equilibrium was examined. An extended Grad-Shafranov equation including toroidal rotation was solved with the FINESSE code [32], using the 70084 pressure and F profiles as input, where $F \equiv B_{tor} R$. For the rotation profiles, scaled variants from 66404

were used such that static ($\gamma_E = 0$), $\gamma_E = 0.3$ and $\gamma_E = 0.6$ cases were studied. All values correspond to $\rho = 0.33$. The different equilibria are seen in Fig.7. The sensitivity of the equilibria to these levels of rotation are found to be small, as expected due to the Mach number squared scaling of the ‘rotation pressure’. Only a 10% increase in the Shafranov shift was observed between the static and $\gamma_E = 0.6$ case. The non-linear predicted flux sensitivity to this different Shafranov shift is also minimal, with only a 6% decrease in ion heat flux when the $\gamma_E = 0.3$ equilibrium is used compared with the static equilibrium for a run with $R/L_{Ti} = 6.9$. We can thus conclude that the effect of rotation on the equilibrium itself can only play a minor role in setting the profile stiffness.

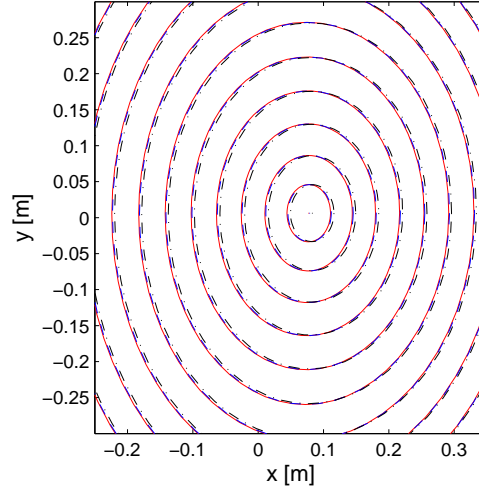


Figure 7. Flux surfaces in the vicinity of the magnetic axis from a solution of the generalised Grad-Shafranov equation using the kinetic profiles of 70084 and scaled rotation profiles from 66404. Three cases are shown: static (red solid curves), $\gamma_E = 0.3$ (blue dashed curves) and $\gamma_E = 0.6$ (black dashed-dotted curves).

3.4. Inclusion of fast particles

The discharges studied have relatively low density, and thus for the higher rotation cases where significant NBI is employed, it is possible that a large fast ion fraction is present. This is predicted to reduce the turbulent drive, since the fast ion species behaves mostly adiabatically due to the higher temperatures, and the density of the main ion species is reduced through dilution. In ASDEX Upgrade strong evidence has pointed to a fast ion dilution mechanism for ITB formation at low density [48]. Monte Carlo simulations of the NBI injection and subsequent fast ion slowing down were carried out for discharge 66404 with NEMO/SPOT [49] within the CRONOS integrated modelling framework. An average fast particle energy ($\approx 35\text{keV}$) at $\rho = 0.33$ was calculated. A linear GENE scan of fast particle densities (relative to n_e) can be seen in Fig.8. In the GENE simulations, the fast particle temperature was approximated to the average fast particle energy value. The scan is carried out for various k_y values in Fig.8a, assuming $R/L_{Tfast} = 0$. The

R/L_{Tfast} sensitivity is examined in Fig.8b at $k_y = 0.4$. A suppression of the growth rates is observed with increasing n_{fast}/n_e . However, for our parameters the fast ion fraction is predicted by NEMO/SPOT to be only $\sim 10\%$, and thus insufficient to strongly affect the growth rates. While a fast ion fraction has been proposed to be responsible for some mismatch between gyrokinetic simulations and experiments [50], in our case it seems that the fast ion fraction may be too low to play a significant role.

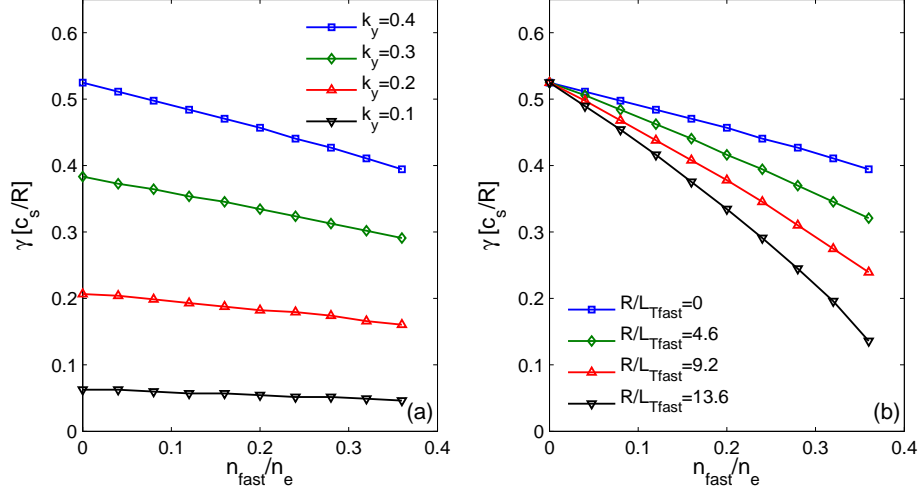


Figure 8. Linear fast particle density scans on 66404 parameters at $\rho = 0.33$ at various values of k_y . Runs were electromagnetic, with collisions, and with numerical geometry.

While the n_{fast}/n_e ratio may be low, the fast particle pressure due to NBI and ICRH can still be a significant fraction of the total pressure. For the NBI driven fast ions in discharge 66404 at $\rho = 0.33$, $P_{fast}/P_{tot} = 0.21$ according to NEMO/SPOT modelling (averaging between 6.5-7.5 s). This leads to an increased Shafranov shift which, particularly at low magnetic shear, can lead to turbulence stabilisation [51]. The effect of the ICRH fast ions on the Shafranov shift was seen to be negligible for this discharge. The increased Shafranov shift can be seen in Fig.9, where the flux surfaces for the low power discharge 70084, and the high power discharge 66404 (with and without the inclusion of the NBI fast particle pressure) are compared. The fast particle contribution to the 66404 Shafranov shift is significant. For 70084, the Shafranov shift is ≈ 7.5 cm. For 66404 with the thermal pressure contribution only, the Shafranov shift is ≈ 8.8 cm. For 66404 with the total pressure (including fast particles), the total Shafranov shift is ≈ 13 cm. The impact of this difference on the predicted fluxes was investigated through dedicated non-linear simulations. The impact was observed to be not negligible but also not a dominating factor. A flux reduction of 15% was observed in the non-linear simulations with $R/L_{Ti} = 8$ when substituting the numerical geometry from 70084 with that of 66404 (i.e. with the fast particle content), as seen in Fig.10. We can thus conclude that the effect of fast particles, through both dilution and an increased Shafranov shift, can reduce the ion heat flux by $\sim 25\%$ when transitioning to

the parameters characterising the ‘low-stiffness’ discharges. This value is not negligible, but cannot be the sole explanation for the reduction in stiffness observed.

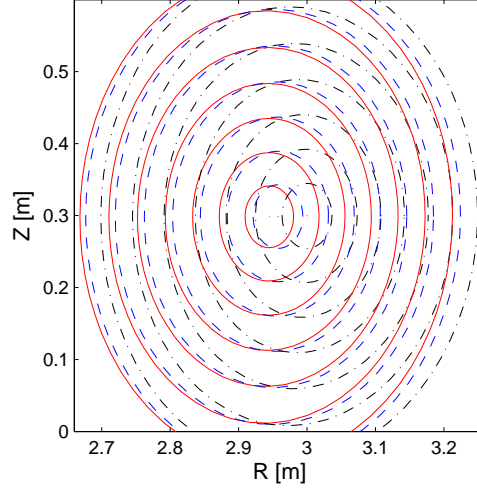


Figure 9. Flux surfaces in the vicinity of the magnetic axis for discharge 70084 (red solid curves), 66404 without fast particle pressure, (blue dashed curves) and 66404 with the inclusion of fast particle pressure (black dashed-dotted curves). $x = y = 0$ corresponds to the geometric axis.

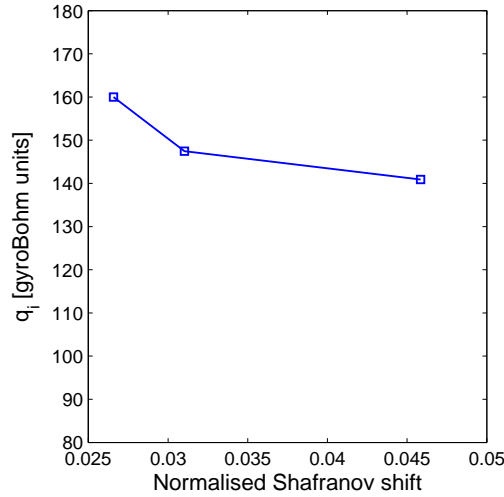


Figure 10. Flux reduction as a function of Shafranov shift normalised to the major radius for the three equilibria presented in Fig.9.

3.5. Impact of R/L_n on the stiffness level

In the limited experimental data set studied, there is a wide variation in R/L_n , from 1.4 in the 70084 case to 3.8 in the 66404 case (which corresponds to the highest R/L_{Ti} in the data set). The sensitivity of the turbulence to the R/L_n value was thus examined. In

particular, the possibility that non-linear ITG-TEM (trapped electron mode) interplay takes place which can reduce the level of turbulence and thus the stiffness, as reported in Ref.[52], was investigated. In Fig.11 these linear scans are shown. For $R/L_n = 1$, the dominant mode propagates in the ion diamagnetic direction (ITG mode). However, for $R/L_n = 3.8$ the mode at low R/L_{Ti} propagates in the electron diamagnetic direction. This is most probably a density gradient driven TEM mode, which is stabilised by R/L_{Ti} (which would correspond to low stiffness) until it switches to an ITG mode at $R/L_{Ti} \approx 5$. At that point we would expect turbulence stabilisation according to Ref.[52]. However, for higher R/L_{Ti} the growth-rate stiffness is similar to the $R/L_n = 1$ case, as a pure ITG regime is reached. For $R/L_n = 5$ the TEM-dominated regime is maintained for much higher R/L_{Ti} . However, the highest experimental R/L_n in the data set of Ref.[25] is $R/L_n \approx 4$. Furthermore, at the experimental high R/L_{Ti} values the transport is ITG dominated and stiff even for $R/L_n = 5$. Thus it is unlikely that R/L_n is responsible for reduced profile stiffness. Furthermore, even if the stiffness is low, the actual growth rates themselves are high, and we may expect a high degree of transport.

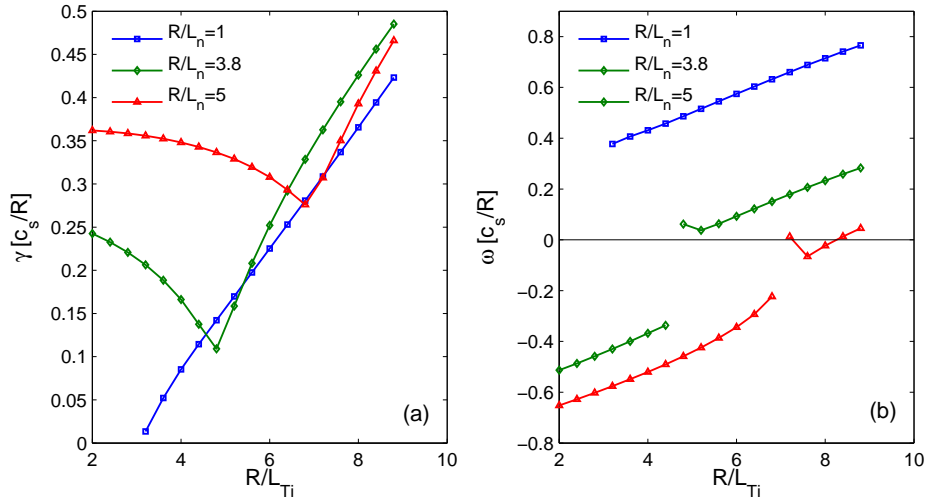


Figure 11. Linear R/L_{Ti} scans based on 66404 parameters at $\rho = 0.33$ with varying R/L_n . Growth rates are shown in (a), and frequencies in (b). Runs were electrostatic, with collisions, and with circular geometry.

These results are maintained in the non-linear scans, seen in Fig.12. While at lower R/L_{Ti} stiffness is indeed reduced in the TEM regime for the high R/L_n case, at higher R/L_{Ti} values the difference in stiffness between the $R/L_n = 1$ and $R/L_n = 3.8$ cases becomes negligible. We can conclude that the variance of R/L_n in the data set is not responsible for the observed difference in stiffness.

3.6. Impact of β_e on the stiffness level

In this subsection the sensitivity of the stiffness on electromagnetic effects - which arise for $\beta_e > 0$ - is examined. The simulations carried out take discharge 66404 parameters

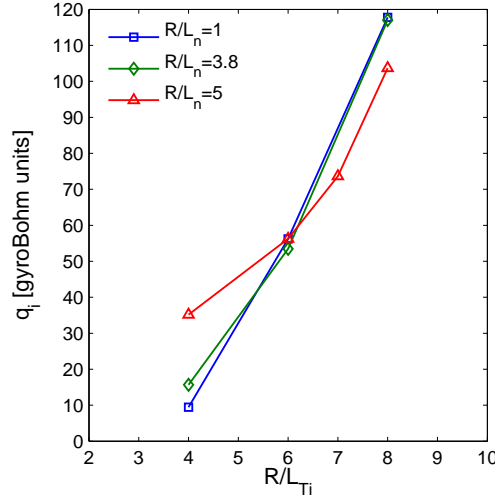


Figure 12. Non-linear R/L_{Ti} scans based on 66404 parameters at $\rho = 0.33$ with varying R/L_n . Runs were electrostatic, with collisions, and with circular geometry.

as a reference. Linear (at $k_y = 0.4$) and non-linear β_e scans are shown in Fig.13. From the linear scans, it is clear that the range of experimental β_e values ($0 - 0.5\%$) are significantly below the kinetic ballooning mode (KBM) thresholds, characterised in the plot by the sharp upturn in growth rates at $\beta_e \approx 1.5 - 2.4\%$; this finding is expected to carry over to the non-linear physics [53]. Below the KBM threshold, β_e stabilises the ITG mode [54]. For our parameters, this leads to a growth rate reduction of $\approx 25\%$ at $\beta_e = 0.5\%$. This is at the upper range of our experimental β_e values. The 25% growth rate stabilisation factor is not exceeded when repeating the linear simulations for $k_y = 0.1 - 0.3$. Interestingly, it appears that the linear ITG mode is stabilised at lower and lower β_e as R/L_{Ti} is increased. For practical purposes, however, this should be of little benefit as the strong background gradient dependence of the β_{KBM} threshold makes any ITG-stable regions irrelevant, since the KBM threshold significantly decreases with R/L_{Ti} .

A striking observation is that the *non-linear* β_e ITG stabilisation significantly exceeds the linear stabilisation. This is consistent with GENE results reported in Refs. [53, 55], as well as, to some degree, with other codes [56, 57]. A decrease in ion heat flux by a factor of 65% is seen in Fig.13b for the $\gamma_E = 0$, $R/L_{Ti} = 9.2$ case between $\beta_e = 0 - 0.48\%$. Simultaneously, while the ion heat flux is reduced by β_e in the $\gamma_E = 0$, $R/L_{Ti} = 4.6$ case, it is not totally quenched. The observation that for $\beta_e > 0$ the flux level is diminished over a range of R/L_{Ti} , yet is not totally quenched in the vicinity of the ITG threshold for $\beta_e = 0$, is indicative that $\beta_e > 0$ (within the range studied) induces a decrease in stiffness as opposed to a threshold shift. Note that the results reported in Ref.[55] cannot be compared with those in Fig.13b quantitatively, as TEM contributions to the overall turbulence picture may change in particular the β_e dependence of the threshold shift.

We can thus conclude that electromagnetic effects play a significant role in stiffness

reduction for our parameters, even at relatively low values of β_e . While this stiffness reduction is not sufficient to fully explain the experimentally observed stiffness reduction, it is a factor which must be taken into consideration.

Additionally, from linear gyrokinetic analysis, β_e stabilisation of ITG modes has been invoked as a possible factor in improved hybrid scenario confinement at ASDEX Upgrade and DIII-D, particularly at outer radii (i.e. beyond half radius) [58]. The increased non-linear β_e stabilisation reported here may point to an even greater importance of this effect than previously recognised. We note that the β_e stabilisation is expected to be effective up to the recently discovered Non-Zonal Transition β_e limit [59], beyond which electromagnetic fluctuations effectively short out the zonal flows and lead to a significant increase in the saturated level of the ITG turbulent fluxes. This β_e threshold very strongly depends on the background gradients, however, and for typical (low) gradients quickly becomes less restrictive than the KBM threshold. Coupled with the fact that this effect produces a limit with enormous stiffness, it can therefore be expected that standard experimental gradient and β_e values in outer radii lie below this point, putting those cases in the β_e stabilisation zone.

In Refs.[53, 55], an increase of the ratio between the zonal flow shearing rate to the unstable mode growth rate (ω_{ZF}/γ) was observed with β_e . A possible physical mechanism for this relative increase in zonal flow activity, based on increased coupling between Alfvénic modes and drift waves, has been suggested [60]. In Fig.14 we plot the mode amplitude spectra for the $\gamma_E = 0$, $R/L_{Ti} = 9.2$ scan over β_e shown in Fig.13. The amplitude spectra have been normalised to the zonal flow (or rather $k_y = 0$, which constitutes a reasonably good measure) amplitudes. Indeed, a relative increase in the $k_y = 0$ modes is seen for the electromagnetic cases, which may be related to the ITG β_e stabilisation. Another possible mechanism for increased zonal flow coupling is the observed widening of the ITG eigenmode structure observed with increasing β_e , as shown in Fig.15. The less ballooned structure facilitates the direct coupling to the poloidally symmetric zonal modes, similarly to what occurs at low magnetic shear [61, 39]. Further work is suggested to shed more light on this topic.

It is interesting to note that the stabilising effect of flow shear is weakened by finite β_e in the higher R/L_{Ti} case, as seen in Fig.13. In the $R/L_{Ti} = 9.2$ case, the effect of flow shear on the turbulence switches from stabilising to destabilising as β_e increases. However, in the $R/L_{Ti} = 4.6$ case flow shear is always stabilising, and no discernible weakening of the stabilisation is seen as β_e increases. Linearly, the PVG modes are not observed to lead to increased stabilisation at increased β_e . More effort needs to be taken in the future to uncover the non-linear effects which either increases PVG destabilisation or decreases the $E \times B$ stabilisation in the high R/L_{Ti} case.

In Fig.16 we can see, from the entire data set in Fig.1 of Ref.[25], the correlations between R/L_{Ti} and β_e for $\rho = 0.33$ and $\rho = 0.64$. There is a generally limited but positive correlation between β_e and R/L_{Ti} at $\rho = 0.33$, consistent with the reduced stiffness. At $\rho = 0.64$, β_e is generally much lower than at $\rho = 0.33$. This is expected to further increase the stiffness at $\rho = 0.64$ as observed experimentally, beyond the

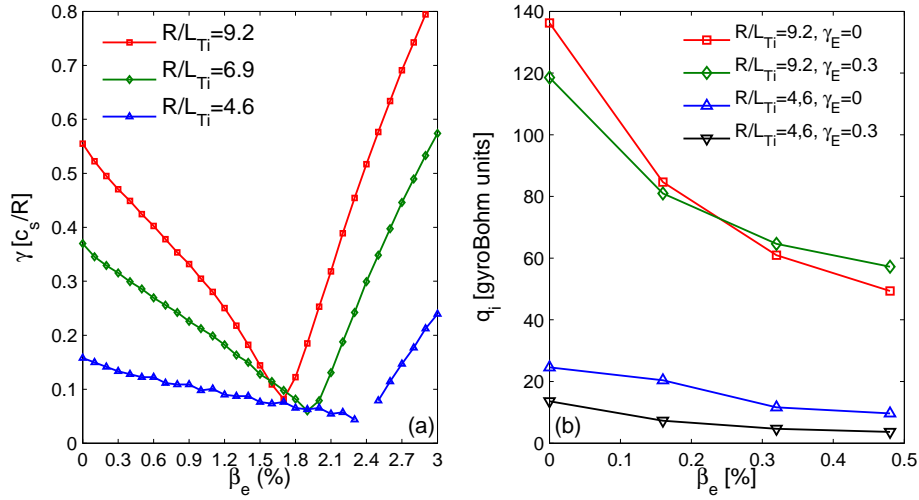


Figure 13. Linear (a) and non-linear (b) β_e scans with 66404 parameters at $\rho = 0.33$. R/L_{Ti} and γ_E are varied. Runs were with collisions and numerical geometry.

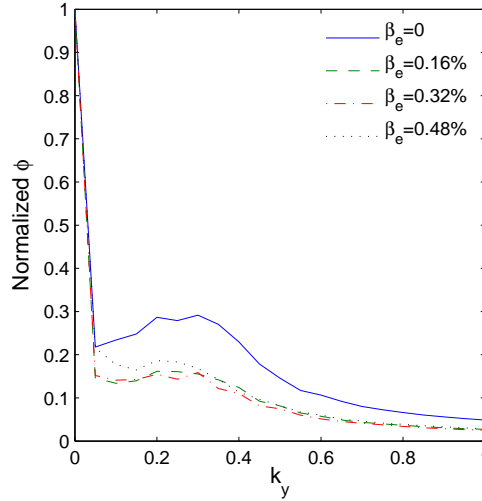


Figure 14. Amplitude spectra from the $\gamma_E = 0$, $R/L_{Ti} = 9.2$, non-linear β_e scan displayed in Fig.13b.

increase solely due to the higher \hat{s} and q values. We note that both at $\rho = 0.33$ and $\rho = 0.64$, a cluster of five points is visible at the highest respective β_e values, separate from the main trend. These points correspond to discharges with significantly more heating power (between 10 – 15 MW of NBI power) and slightly lower magnetic field (3 T as opposed to 3.4 T) than the rest of the dataset. The scatter that these points induce to the correlation between β_e and R/L_{Ti} is indicative of the difficulty in making a pure comparison of the effect of β_e throughout the dataset, due to the concomitant changes in other plasma parameters and normalized ion heat fluxes.

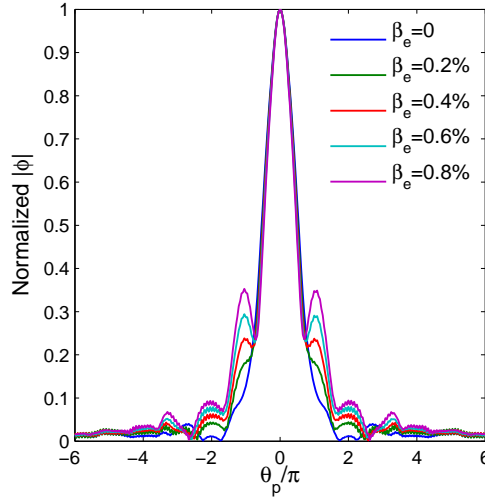


Figure 15. β_e scan of ITG eigenmode structure calculated by linear-GENE. $R/L_{Ti} = 9.2$, and $\gamma_E = 0$.

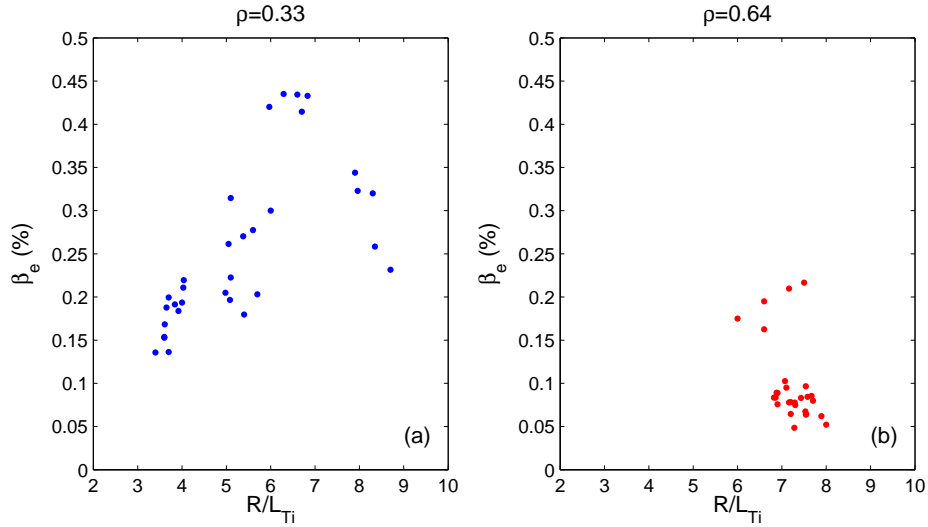


Figure 16. Correlation between R/L_{Ti} and β_e at $\rho = 0.33$ (a) and at $\rho = 0.64$ (b) from the entire data-set presented in Ref.[25].

3.7. Full simulations including all effects

Simulations of all four discharges in the data set at $\rho = 0.33$ were carried out. We analyse the ‘high-stiffness-branch’ and ‘low-stiffness-branch’ separately in sections 3.7.1 and 3.7.2 respectively. Ion heat fluxes from non-linear simulations and experimental power balance are compared. The simulations included flow shear, the effect of rotation on equilibrium, experimental R/L_n , finite β , collisions, $Z_{eff} > 1$, and experimental T_e/T_i . The effect of Z_{eff} - which is stabilizing for ITG turbulence - was modelled by lumping all impurities into a kinetic fully stripped carbon ion species. The carbon temperature, R/L_T , and R/L_n were assumed the same as the main deuterium species. Simulations

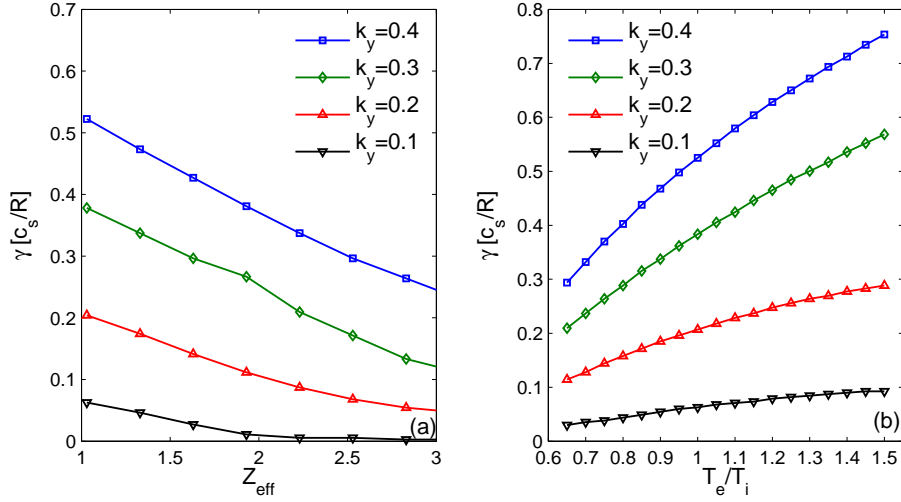


Figure 17. Sensitivity of growth rates to Z_{eff} (a) and T_e/T_i (b) from linear GENE runs based on 66404 parameters at $\rho = 0.33$. Runs were electromagnetic, with collisions, and with numerical geometry.

with varying Z_{eff} values were carried out, to test the sensitivity of the predictions to the uncertainties in the Z_{eff} profile shape. The growth rate sensitivity to Z_{eff} and T_e/T_i for linear GENE runs based on discharge 66404 can be seen in Fig.17. For our cases, the Z_{eff} stabilisation tends to be compensated by the $T_e/T_i > 1$ destabilisation. In the non-linear simulations, assuming $R/L_{Tc} = 0$ for the carbon species instead of $R/L_{Tc} = R/L_{Ti}$ altered the bulk ion heat flux by less than 2%. While the impact of the fast ions on the Shafranov shift is included in the simulations, fast ion dilution of the main ion species was not included. It was judged that the relatively minor ($\sim 10\%$) impact of this effect on the simulated flux values did not justify the inclusion of the fast ions as a separate ion species in the simulations, which significantly slow down the calculations.

3.7.1. Investigation of the low-rotation, high-stiffness branch In section 3.1, figure 4, it is evident that the stiffness of the simulated $\hat{s}/q = 0.7/1.7$ curve is less than the apparent experimental trend. In this section, we examine the possibility that the higher T_e/T_i of the high flux discharge 73221 in the low rotation branch is responsible for the increased flux, through the T_e/T_i impact on the ITG critical threshold. It is important to note that this significant difference in T_e/T_i between the high and low flux discharges in the low-rotation branch was not apparent when the data was analysed in Refs. [24, 25]. Since that time, the ECE data has been recalibrated.

A $R/L_{Tcrit} \propto (1 + T_i/T_e)$ scaling has been derived both analytically and from linear gyrokinetic simulations for the ITG instability [2, 38]. A decreased instability threshold leads to increased flux for a given R/L_{Ti} value, as long as the stiffness level does not change with T_e/T_i . It has been predicted by non-linear simulations that the stiffness level is not sensitive to T_e/T_i within the range relevant for our studied discharges [62].

The simulation results for the 70084 and 73221 discharges are shown in figure 18. Since R/L_{Ti} is close to threshold and the transport is relatively stiff, the results are highly sensitive to the input parameters. Additionally, the proximity to threshold leads to statistical flux variations due to intermittency often higher than the typical 5 – 10% level observed for the simulations in this paper. These variations are displayed on the plot for these specific cases. For 70084, agreement between the non-linear simulation and the experimental observation was found for reasonable departures from the base parameters recorded in table 2. R/L_{Ti} and T_e/T_i were both taken at the high end of their error bars. Z_{eff} was taken as 1.4, lower than $\langle Z_{eff} \rangle = 2.2$. This is a reasonable assumption since the Z_{eff} profiles tend to be hollow, and $\rho = 0.33$ is relatively close to the magnetic axis. Making the same assumptions for 73221 (although maintaining the base value of T_e/T_i), the simulated flux value was found to be significantly lower than the experimental value. Even though T_e/T_i is higher in 73221 than in 70084, the impact of the higher T_e/T_i on the ITG critical threshold is compensated by the lower q value calculated by the 73221 CRONOS interpretative simulation compared with 70084. However, when increasing the 73221 q value in the simulation to equal the 70084 value - an increase of only $\sim 15\%$ - the simulated flux value then becomes comparable to the experimental value. When assuming the Faraday rotation constrained EFIT q -profile for 73211, with $\hat{s}/q = 0.5/1.4$, we obtain an intermediate flux level between the 70084 and 73221 experimental flux values. These tests of the 73221 to the variations of q and \hat{s} constitute a sensitivity analysis of the fluxes to reasonable estimates of the q -profile error bar. We thus deem that the T_e/T_i increase of the high flux cases in this branch compared with the low flux cases is a likely explanation for the seeming anomalously high stiffness of this data-set. However, the high sensitivity of the simulated flux - through the impact on the critical threshold - to T_e/T_i and the q -profile variations within the estimated experimental error bars precludes a firm conclusion on this point. The result lies within the uncertainties - particularly of the q -profile calculations. In table 3 we show the results for all simulations carried out for 70084 and 73221 - beyond those shown in Fig. 18. The sensitivities of the flux to input parameters such as \hat{s} , q , Z_{eff} , γ_E , and R/L_n are shown. We note that the results are *not* highly sensitive to wide variations in the R/L_n values.

3.7.2. Investigation of the high-rotation, low-stiffness branch The comparison between the GENE non-linear simulations and the experimental heat fluxes for the ‘low-stiffness branch’ is shown in Fig.19. For the high rotation discharges, three separate sets of simulations are shown: with the q -profile from the CRONOS interpretative runs and $Z_{eff} = 1.9$, with the optimistic $\hat{s}/q = 0.2/1.3$ assumption and $Z_{eff} = 1.9$, and finally with the optimistic $\hat{s}/q = 0.2/1.3$ assumption and $Z_{eff} = 2.4$. The input parameters and flux values for these simulations, as well as additional simulations carried out for further sensitivity studies and for clarity not shown in Fig.19, are listed in table 4.

For the $R/L_{Ti} = 6$ discharge 66130, the simulation with the base parameters (i.e. with the CRONOS \hat{s} and q values) leads to a flux value $\times \sim 2.5$ above the experimental

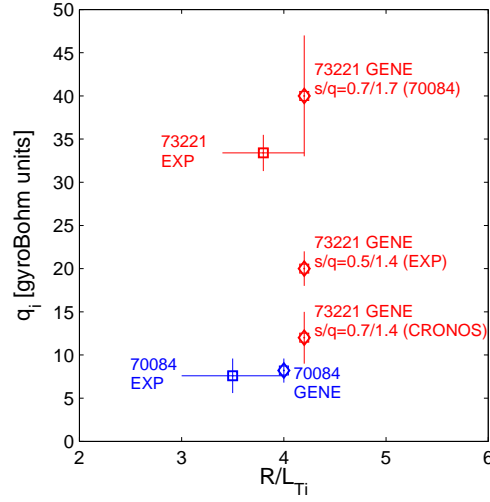


Figure 18. Comparison of experimental and simulated ion heat flux for discharges 70084 and 73221 situated on the ‘high-stiffness-branch’ at $\rho = 0.33$ from the dataset of Ref.[25]. The 73221 simulation results shown were carried out for three separate \hat{s}/q values to test the sensitivity to the q -profile uncertainties.

Table 3. Input data and ion heat flux results for discharge 70084 and 73221 non-linear simulations. The cases in bold font are the simulations displayed in Fig. 18.

Shot number	Z_{eff}	R/L_{Ti}	R/L_n	T_e/T_i	γ_E	\hat{s}	q	q_i [gyroBohm units]
70084	1.4	3.5	1.4	1.12	0.07	0.7	1.7	0
70084	1.4	4	1.4	1.12	0.1	0.2	1.3	0
70084	1.4	4	1.4	1.12	0.1	0.7	1.7	8.2 ± 1.4
70084	1.4	4	1.4	1.12	0.07	0.7	1.7	14 ± 4
70084	1.4	4	1.4	1.08	0.1	0.7	1.7	0
70084	1.9	4	1.4	1.12	0.07	0.7	1.7	0
70084	1.9	4	1.4	1.12	0.04	0.7	1.7	7.5 ± 1.5
73221	1.4	4.2	2.8	1.35	0.02	0.7	1.4	12 ± 3
73221	1.4	4.2	1.0	1.35	0.02	0.7	1.7	48 ± 2
73221	1.4	4.2	2.8	1.35	0.02	0.7	1.7	40 ± 7
73221	1.4	4.2	3.8	1.35	0.02	0.7	1.7	31 ± 7
73221	1.4	4.2	2.8	1.35	0.02	0.5	1.4	20 ± 2
73221	1.9	4.2	2.8	1.35	0.02	0.7	1.4	1.7 ± 0.3
73221	1.9	4.2	2.8	1.35	0.02	0.7	1.7	13 ± 3

Table 4. Input data and ion heat flux results for discharge 66130 and 66404 non-linear simulations. The cases in bold font are the simulations displayed in Fig. 19.

Shot number	Z_{eff}	R/L_{Ti}	T_e/T_i	\hat{s}	q	q_i [gyroBohm units]
66130	1.4	6	1.25	0.2	1.3	19.4
66130	1.4	6	1.12	0.2	1.3	12.3
66130	1.9	6	1.25	0.7	1.8	31.3
66130	1.9	6	1.25	0.2	1.3	11.1
66130	2.4	6	1.25	0.2	1.3	7.5
66404	1.4	8.6	1.14	0.2	1.3	53.2
66404	1.9	8.6	1.14	0.4	1.8	77.1
66404	1.9	8.6	1.14	0.2	1.3	33
66404	2.4	8.6	1.14	0.4	1.8	47
66404	2.4	8.6	1.14	0.2	1.3	23.8
66404	2.4	7.7	1.08	0.2	1.3	13.7

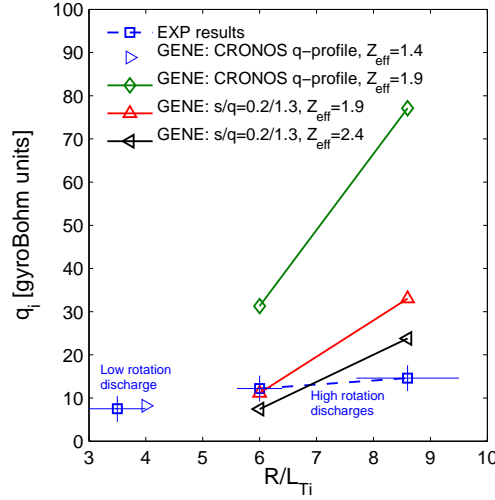


Figure 19. Comparison of non-linear simulations and experimental results for the three separate discharges at $\rho = 0.33$. For the high rotation discharges, various sets of simulations with varying \hat{s} , q , and Z_{eff} assumptions are shown. The GENE simulations corresponding to the low and high rotation discharges were carried out with $\gamma_E = 0.1$ and 0.3 respectively.

level. This discrepancy can be reduced by a reasonable variation of input parameters around the experimental uncertainties, either for q and \hat{s} , Z_{eff} , or R/L_{Ti} . However, the discrepancy between the simulation and the experimental flux for the higher $R/L_{Ti} = 8.6$ discharge - 66404 - is significantly greater. For the simulation with the base input parameters, the simulated flux is $\times \sim 5$ higher than the experimental value. The simulated and experimental flux can only be reconciled by making a highly optimistic assumption with regard to the simultaneous variation of R/L_{Ti} , Z_{eff} , \hat{s} , q , and T_e/T_i around their estimated error bars - as seen in the last line of table 4. This is a highly unlikely scenario, and leads us to conclude that the stiffness in these specific gyrokinetic simulations is higher than the experimental observations for the high-rotation branch.

The predicted and experimental fluxes for 66404 can however be reconciled by both artificially increasing γ_E beyond the measured value from the toroidal rotation, and simultaneously ignoring PVG destabilisation. This is shown in an additional set of simulations displayed in Fig.20. This assumption is consistent with assuming non-negligible poloidal rotation. Our original assumption of negligible poloidal rotation due to neoclassical damping was justified by NCLASS [63] neoclassical poloidal rotation predictions for the deuterium species within the CRONOS modelling. This is seen in Fig.21, where the γ_E profiles derived from the NCLASS predicted poloidal rotation are shown. While there is an increase in γ_E correlated with increasing R/L_{Ti} as expected, the absolute values are - while not entirely negligible for the 66130 and 66404 cases - still approximately an order of magnitude below the values necessary to provide significant turbulence suppression as observed. However, poloidal rotation values significantly above neoclassical values have been observed within internal transport

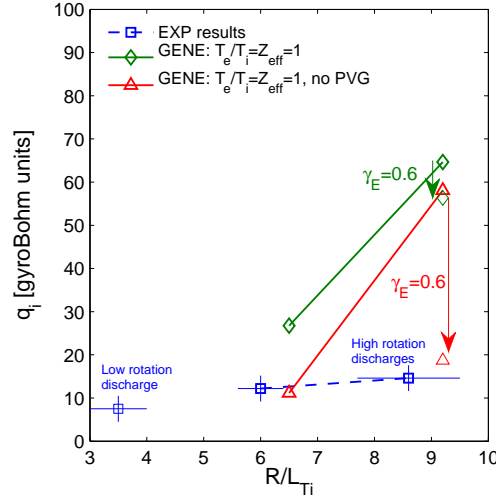


Figure 20. Comparison of flux values from non-linear simulations and experimental power balance for the high rotation discharges 66130 and 66404. Here we assumed for simplicity $T_e/T_i = Z_{eff} = 1$. Sets of simulations both including and excluding the PVG drive are shown. For each set, additional 66404 simulations with γ_E increased from 0.3 to 0.6 were carried out.

barriers (ITBs) [10]. NCLASS predictions have also been shown to deviate from experimentally measured carbon poloidal rotation values at DIII-D [64]. Also at DIII-D, the directly measured differences between core main ion and impurity toroidal rotation are observed to be inconsistent with the neoclassical predictions in cases with steep pressure gradients [65]. For our study, this questions both the validity of the negligible poloidal rotation assumption and also the inference of the main ion rotation level from the impurity rotation measurements. It is thus of interest to directly measure poloidal rotation in the low-stiffness-regime discharges, to examine whether nonetheless any anomalous poloidal rotation is observed. It is also of interest to examine a theoretical mechanism for generation of anomalous poloidal flow - potentially via a turbulent Reynolds stress- particularly for cases with a high degree of external toroidal momentum injection.

The dramatic decrease in flux seen in the 66404 case when transitioning from $\gamma_E = 0.3$ to $\gamma_E = 0.6$ in the no-PVG case in Fig.20 can be understood as a consequence of the suppression of lower k_y modes. In Fig.22, a 2D linear R/L_{Ti} and k_y scan of growth rates for discharge 70084 (including realistic parameters) is shown. 70084 is shown instead of 66404 for this illustration since the ITG behaviour is similar but the TEM driven modes at low R/L_{Ti} in the 66404 case complicates the picture without changing the qualitative message. No rotation was included in the scan. The contours for $\gamma = 0$ (linear threshold), $\gamma = 0.15$ and $\gamma = 0.3$ are highlighted in white. Modes with growth rates up to $\gamma = 0.15, 0.3$ can be expected to be suppressed by $\gamma_E \approx 0.3, 0.6$ respectively. Low k_y modes drive a significant amount of flux, as represented by the γ/k^2 mixing length argument. In Fig.22, the estimated low k_y cutoff due to a flow shear of $\gamma_E = 0.6$ is thus $k_y \sim 0.3$. In that regime, the flux should be significantly reduced

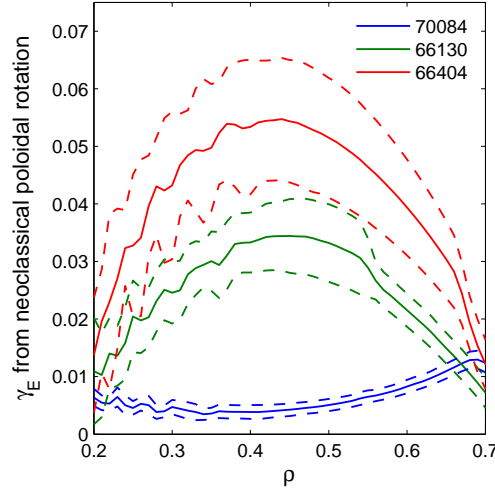


Figure 21. γ_E derived from the NCLASS predicted poloidal rotation for deuterium. The solid lines are the average values over the 1 s time window studied for each case. The dashed lines corresponded to the standard deviation of the profiles around the mean during the time window.

since the high-flux-inducing low k_y modes are sheared out of the system. Indeed, when comparing the flux spectra maxima for the $\gamma_E = 0.3$ and $\gamma_E = 0.6$ no-PVG non-linear cases, the maxima are at $k_y = 0.25$ and $k_y = 0.35$ respectively, in line with the intuition gained from the linear runs.

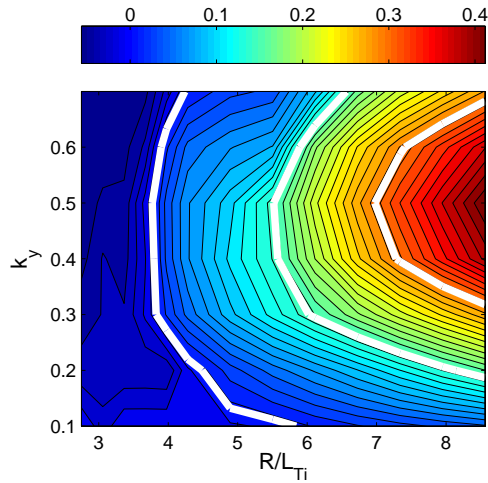


Figure 22. 2D plot of growth rates as a function of R/L_{Ti} (x-axis) and k_y (y-axis) for discharge 70084 with realistic parameters - identical to the non-linear case in Fig.19. The growth rates are in units of $[c_s/R]$. The three white contours correspond to $\gamma = 0, 0.15, 0.3$ from left to right respectively.

We now summarise the entire discussion on the low-stiffness question. The predicted impact of the differences in parameters between the low and high rotation discharges at $\rho = 0.33$ were examined in detail with linear and non-linear gyrokinetic simulations to

investigate the potential factors leading to the observed reduced stiffness in the high-rotation cases. It was found that the differences in R/L_n and the effect of rotation on the equilibrium have negligible impact on the stiffness for our parameters. The effect of rotation itself, and of the fast particle content in the high rotation cases, have non-negligible but insufficient impact to explain the observed difference in rotation. The impact of q and \hat{s} on the stiffness level is however significant. The non-linear stabilisation of ITG turbulence due to electromagnetic effects (β_e) was significant, but by itself still insufficient to explain the full stiffness reduction. When self-consistently including all effects, the ion heat flux values predicted by the gyrokinetic simulations agreed with the observed values in the low rotation case (70084), and were $\times \sim 2.5$ and $\times \sim 5$ higher for the high rotation cases 66130 and 66404 respectively. For reasonable variations of the input parameters around their uncertainties, the simulated and experimental flux values for 66130 could be reconciled. However, for 66404 (which is the highest R/L_{Ti} case), the discrepancy between the simulation and the observation could not be reconciled by a reasonable variation of the input parameters. Improved agreement for 66404 could however be obtained by assuming both a γ_E value higher than measured from the toroidal rotation profile, and simultaneously suppressing parallel velocity gradient destabilisation. These assumptions are consistent with non-negligible poloidal rotation, which is an unmeasured quantity for these discharges. Poloidal rotation gradients approximately an order of magnitude higher than the predicted neoclassical values would be necessary to achieve sufficient impact. Carrying out poloidal rotation measurements for this class of discharge is thus recommended, as is the analytical and numerical investigation of potentially significant turbulent generation of poloidal flow in the relevant parameter regime of these discharges.

4. Simulations at $\rho = 0.64$

In the previous section, the possible factors leading to a *difference* in stiffness between the low and high rotation discharges at $\rho = 0.33$ was investigated. In this section we investigate the experimental observation of a *lack* of stiffness reduction with rotation between the classes of discharges at $\rho = 0.64$, which attained similar R/L_{Ti} values, as seen in Fig.1b. Non-linear simulations with GENE of three of the discharges were performed, with parameters matching those at $\rho = 0.64$. First, reduced simulations are carried out based on 70084 parameters, varying the rotation alone and examining its impact on R/L_{Ti} and the stiffness. Then, full simulations are carried out - analogous to those in section 3.7 - and the GENE predicted ion heat fluxes are compared with the experimental values.

In Fig.23 a non-linear R/L_{Ti} scan with various levels of γ_E is shown. The scan is based on discharge 70084 parameters, but uses circular geometry, $\hat{s}/q = 2/3$, and is collisionless and electrostatic. The simulated stiffness is indeed greater than the $\rho = 0.33$ case shown in Fig.5 as can be seen in a direct comparison shown in Fig.24 for the $\gamma_E = 0$ case. Moreover, the degree of experimental γ_E variation between the discharges (between

$\gamma_E = 0.1 - 0.3$) is also not sufficient to lead to a significant difference in R/L_{Ti} for the same level of flux.

Examining the differences in experimental parameters for all 3 discharges between $\rho = 0.33$ and $\rho = 0.64$ in table 2, we can see that both \hat{s} and q are higher at $\rho = 0.64$, and β_e is lower. All of these differences are expected to lead to higher stiffness in the $\rho = 0.64$ cases compared with $\rho = 0.33$. These qualitative differences in q -profile and β_e between low and high radii are generic (apart from special cases such as in ITB discharges), and should hold in general in tokamak discharges.

In Fig.25, the full comparison between the simulations and the experiments is shown. These gyrokinetic simulations are electromagnetic, collisional, with numerical geometry, include a carbon species at a density consistent with $Z_{eff} = 1.9$ for 66130, and $Z_{eff} = 2.4$ for 70084 and 66404. The simulations include the experimental T_e/T_i . For all cases, the simulated and experimental ion heat flux agree approximately within 50%. This magnitude of difference can be easily reconciled within the reasonable uncertainties of input modelling parameters such as R/L_{Ti} , T_e/T_i or Z_{eff} , particularly for these stiff transport cases. An R/L_{Te} sensitivity check for discharge 66130 was carried out, which had the largest relative R/L_{Te} error throughout the data set, as seen in table 2. It was found from the dedicated non-linear simulations that within the possible R/L_{Te} range the impact on ion transport is minimal.

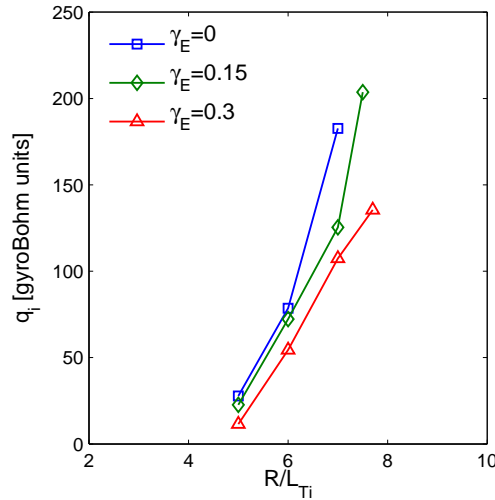


Figure 23. Non-linear R/L_{Ti} scan for various levels of γ_E , based on the 70084 parameters at $\rho = 0.64$. Circular geometry, $\hat{s}/q = 2/3$, collisionless and electrostatic.

To summarise, the effect of rotation alone at $\rho = 0.64$ is not expected to lead to experimentally discernible differences in R/L_{Ti} and stiffness for the range of experimental γ_E examined. This is in agreement with the experimental trend seen in Fig.1b. When comparing the full non-linear gyrokinetic ion heat flux predictions with the experimental values at $\rho = 0.64$, general agreement within reasonable input parameter uncertainties is seen for all the discharges, both at high and low rotation.

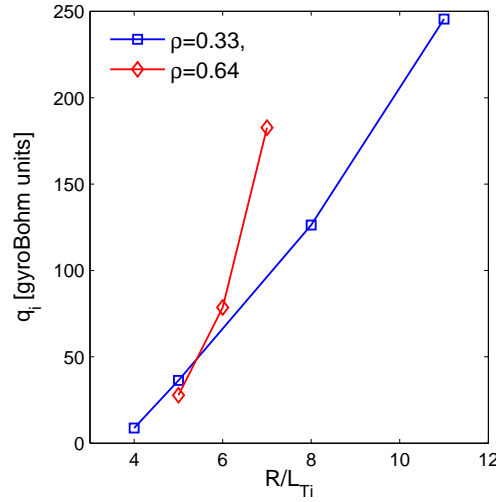


Figure 24. Non-linear R/L_{Ti} scan comparing the stiffness level at $\rho = 0.33$ and $\rho = 0.64$, at $\gamma_E = 0$, based on the 70084 parameters. Circular geometry, collisionless, and electrostatic.

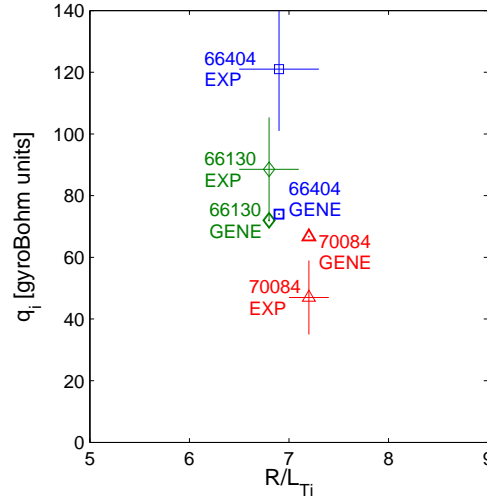


Figure 25. Comparison between gyrokinetic simulations and experiment at $\rho = 0.64$ for all three discharges. The experimental values (with the error bars) are shown for 70084 (red marker), 66130 (green marker) and 66404 (blue marker). The simulated values are shown with the same colour coding and marker style for all three discharges. Runs were electromagnetic, with collisions, and with numerical geometry.

5. Conclusions

Observations at JET have shown evidence of reduced ion temperature profile stiffness correlated with low magnetic shear and increased flow shear. The same data-set has also raised questions regarding the experimental validation of the Dimits shift paradigm, and the low-rotation subset of discharges within this data-set seemed to display *higher* profile stiffness than expected from gyrokinetic simulations. These observations have motivated extensive non-linear gyrokinetic simulations to investigate these questions. Simulations

using the GENE code were carried out, with parameters based on a subset of these JET discharges. Transport sensitivity scans of various parameters that differed between the discharges - aside from rotation - were carried out, to assess potential mechanisms that may explain the observations. Full simulations including electromagnetic effects, numerical geometry, Z_{eff} , experimental T_e/T_i , and rotation were also performed at $\rho = 0.33$ (in the low stiffness zone) and $\rho = 0.64$ for the discharges studied. The predictions were compared with the experimental results. The conclusions can be summarised as follows:

- (1) For the low rotation cases at $\rho = 0.33$, agreement between the gyrokinetic simulations and the experimental ion heat fluxes could be obtained within reasonable variations of the input parameters within their uncertainties. For the high rotation discharges, such agreement could also be obtained for the intermediate $R/L_{Ti} = 6$ case, but not for the high $R/L_{Ti} = 8$ case. Thus, according to the gyrokinetic simulations, the measured values of toroidal flow shear are insufficient to explain the full transition to the low stiffness regime. While the competition between parallel velocity gradient (PVG) destabilisation and $E \times B$ stabilisation can reduce the stiffness in the vicinity of the turbulence threshold, the predicted flux levels themselves are still significantly higher than the experimental values. Improved agreement between the simulation and observation for the $R/L_{Ti} = 8$ case is however obtained when both ignoring PVG destabilisation, and assuming γ_E values above the measured values. These rotation settings are consistent with non-negligible poloidal rotation, which we have assumed to be negligible due to neoclassical damping. It is thus of interest to examine both experimentally and theoretically the possibility of anomalous poloidal rotation in this regime, potentially due to a turbulent Reynolds stress in the presence of external toroidal momentum input.
- (2) The transport sensitivity to R/L_n variations, dilution due to fast particles, increased Shafranov shift due to suprathermal pressure, and the effect of rotation on the equilibrium, were all examined. It was established that none of the above factors are sole mechanisms for the transition to the reduced stiffness regime. Their cumulative effect is however not negligible - particularly that of fast particles both through dilution and an increased Shafranov shift.
- (3) The sensitivity of the transport to β_e was examined. It was established that even for the relatively low β_e values present in these discharges, the non-linear electromagnetic ITG stabilisation is significant. This stabilisation, at least for $\beta_e < 0.48\%$, is a stiffness reduction as opposed to a threshold shift. The non-linear stabilisation is significantly greater than the linear β_e stabilisation, and may be related to an increased relative amplitude of zonal modes. Further investigations of the parameterisation of this effect is important for incorporation into the 'mixing length rule' of quasilinear transport formulations. It is expected that this effect would, using such formulations, lead to more optimistic predictions for the energy confinement in future devices such as ITER and DEMO, which are not expected to

have significant rotation but could still benefit from β_e stabilisation.

- (4) No clear disagreement is observed between the experimentally observed turbulence R/L_{Ti} threshold and the upshifted (Dimitis shift) non-linear threshold predicted by the gyrokinetic simulations. Previously reported results of such a disagreement in Refs. [24, 25] were found to be highly sensitive to the precise choice of q values used for the simulations. Recently improved data processing methodology has led to a revised q value now seemingly pointing to the opposite result of good agreement between the experimentally observed and simulated threshold values. However, a firm conclusion on this point is not justified considering the sensitivity of the results to both q and \hat{s} .
- (5) For the low-rotation branch at $\rho = 0.33$ within the data-set studied, the observation of seemingly anomalous high stiffness compared with the gyrokinetic simulations is likely explained by a downshift in the ITG critical gradient due to higher T_e/T_i in the high flux cases. However, a firm conclusion in this regard is precluded by the high sensitivity of the critical gradient to q and \hat{s} , and thus to the q -profile uncertainties.
- (6) The gyrokinetic predictions and experimental fluxes were also compared at $\rho = 0.64$ for the three discharges. The experimental variation in flow shear between the discharges was not predicted to be sufficient to lead to a discernible difference in R/L_{Ti} - in agreement with the observations. The simulated and experimental ion heat fluxes for all examined discharges all agreed to within approximately 50%. This degree of discrepancy can be explained by reasonable variations of the input parameters within the experimental uncertainties.

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